High-Frequency Sound Interaction in Ocean Sediments: Environmental Controls

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LONG-TERM GOALS

Our long-term objectives are to provide a fundamental understanding of high-frequency acoustic-bottom interactions sufficient to predict acoustic scattering from the seafloor, penetration of acoustic energy into the seafloor, and propagation of acoustic energy within the seafloor. These acoustic models support performance prediction and tactical use of MCM sonar including buried mine detection by Synthetic Aperture Sonar (SAS), and also support shallow water ASW sonar systems.

OBJECTIVES

Provide statistical characterization of the environmental properties, especially the sediment volume properties, required to determine and model the dominant mechanisms controlling the penetration into and scattering from the seafloor of high-frequency acoustic energy. Determine the effects of biological, geological, biogeochemical, and hydrodynamic processes on the spatial distribution of sediment physical, geotechnical and geoacoustic properties at the experimental site. Develop predictive empirical and physical models of the relationships among those properties.

APPROACH

Participate in the SAX04 high-frequency acoustic experiments in the northeastern Gulf of Mexico. Provide statistical characterization of the environmental properties, especially the roughness and sediment volume properties, required to understand, model, and determine the relative importance of the dominant mechanisms controlling both penetration of high-frequency acoustic energy into the seafloor and scattering of high-frequency energy from the seafloor. Special emphasis is placed on the effect of sand ripples on SAS detection of buried targets. Measure and model the dispersive behavior of sediment sound speed and attenuation over the 1-400 kHz frequency band. Conduct in situ manipulative experiments to determine the effects of changing seafloor roughness and the presence of discrete scatterers on high-frequency acoustic scattering. Determine the effects of biological, geological, and hydrodynamic processes on the spatial and temporal distribution of sediment physical,

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14. ABSTRACT

Our long-term objectives are to provide a fundamental understanding of high-frequency acoustic-bottom interactions sufficient to predict acoustic scattering from the seafloor, penetration of acoustic energy into the seafloor, and propagation of acoustic energy within the seafloor. These acoustic models support performance prediction and tactical use of MCM sonar including buried mine detection by Synthetic Aperture Sonar (SAS), and also support shallow water ASW sonar systems.

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geotechnical and geoacoustic properties. Develop predictive empirical and physical models of the relationships among those properties. Derive a fundamental understanding of the effects of sediment microstructure (porometric and grain properties) on fluid flow and geoacoustic properties.

WORK COMPLETED

The Seafloor Sciences Branch of the Naval Research Laboratory concentrated efforts on the participation in ONR Sediment Acoustic Experiments (SAX04) in the northeastern Gulf of Mexico during CY2004. The role of the Naval Research Laboratory is to provide statistical characterization of the environmental properties, especially the physical and geoacoustic properties, roughness, and sediment volume properties, required to understand, model, and determine the relative importance of the dominant mechanisms controlling both penetration of high-frequency acoustic energy into the seafloor and scattering of high-frequency energy from the seafloor. Special emphasis was placed on the effect of sand ripples on SAS detection of buried targets by the Applied Physics Laboratory (APL) at the University of Washington. We also measured and modeled the dispersive behavior of sediment sound speed and attenuation over the 1-400-kHz frequency band. In situ manipulative experiments were conducted to determine the effects of changing seafloor roughness on high-frequency acoustic scattering and to characterize and model the effects of biological, geological, and hydrodynamic processes on the spatial and temporal distribution of sediment properties, especially the effects of biological processes on rates of degradation of sand ripples. These data will be used to improved predictive empirical and physical models of the relationships among those properties and to derive a fundamental understanding of the effects of sediment microstructure (porometric and grain properties) on fluid flow and geoacoustic properties.

ENVIRONMENTAL MEASUREMENTS: Based on acoustic modeling requirements, values of the following sediment properties were measured during or following SAX04:

• Sediment grain properties: grain size distribution, shape and surface texture, and grain density

• Water properties: density, bulk modulus, viscosity, compressional speed measured and calculated from pore water temperature, salinity and pressure

• Porometry: porosity, pore body size distribution, pore shape, pore throat size distribution, pore body-pore throat correlations, grain contacts, permeability

• Sediment porosity and water content

• Sediment shear and compressional speed and attenuation

• 1-D seafloor roughness (spatial and temporal variations)

• The distribution of discrete scatterers such as shells

Properties such as shear and compressional wave speed and attenuation, and seafloor roughness were measured in situ. Frame bulk and shear moduli and log decrements will be estimated from measured sediment geoacoustic properties. Measurement scales required to statistically characterize the heterogeneity of sediment properties such as bulk density, compressional wave speed and attenuation,

and bottom roughness depend on the frequency of the acoustic phenomena being investigated: as small as a quarter of an acoustic wavelength or as small as 1 cm for penetration experiments and as small as 1 mm for scattering experiments.

RESULTS

Seafloor property measurements: Divers collected a total of 58 5.9-cm-diameter cores from throughout the experiment area in order to characterize the means and the spatial and temporal variability of geoacoustic and physical properties in the SAX04 experimental area. In the sand sediment, values of sound speed (at 23°C, 35 ppt, atmospheric pressure) or sound speed ratio (mean = 1775.6 m s^{-1}; 1.162) and attenuation (mean = 0.23 dB m^{-1} kHz^{-1}) were within the range of values measured in other sandy sediments including sediments collected during the SAX99 experiments. Lower values of sound speed were associated with muddy flaser deposits. Sound speed increased slightly with depth in the top 10 cm and, exclusive of the flaser deposits, had an overall coefficient of variation of 0.55 %. Values of attenuation varied little with depth and were slightly lower than for sediment collected during SAX99 (mean = 0.43 dB m^{-1} kHz^{-1}). The lowest values of attenuation were measured within mud lenses and the highest values of attenuation were measured at interfaces between mud lenses and sand.

Following the measurement of sediment sound speed and attenuation, 22 cores were selected for sectioning at 2-cm intervals for determination of sediment porosity, bulk density, and grain density; 16 of these sectioned cores were analyzed for grain size distribution. In the sand, porosity (mean = 36.7 %) and bulk density (mean = 2.064 g cm^{-3}) varied little with depth. Sand mean grain size (mean = 1.48 phi) was similar to sediment collected during SAX99 (mean = 1.27 phi). Additional 13-cm-long cores were collected by divers for sediment permeability determination. Values of hydraulic conductivity varied from 0.56 to 4.65 x 10^{-2} cm s^{-1} (approximately 0.53 to 4.34 x 10^{-11} m^2 in units of intrinsic permeability). The higher values of permeability were associated with cores with mud lenses. Sediments without mud layers had roughly the same permeability (0.93 to 4.56 ×10^{-2} cm s^{-1}) as sediments collected during SAX99.

Several of the long diver cores were impregnated on board ship with resin after measurement of acoustic properties. These cores have been scanned using a high-resolution CT-scanner in order to quantify fine-scale density heterogeneity, especially related to the distribution and structure of the mud flasers and sand laminae. Later analysis of CT-images will be used to quantify fine-scale pore and grain structure, measure tortuosity, and enumerate and describe grain contacts (Fig. 1). These data will be used to model acoustic behavior using contact mechanics and to calculate permeability using percolation and effective media theory.

A vibracore survey to the SAX04 site was conducted during July and August 2005 and recovered cores from 15 locations. A coarse layer (perhaps shell) approximately 1.5 m below the sea floor existed throughout the study area and restricted penetration. Despite the coarse layer obstacle, sample recovery ranged between three and five meters depth in the sediment. These cores await X-ray stratigraphic analysis, sound speed logging, and grain size distribution measurement.

Pore water was collected by divers with a 30-cm-long cannula. Salinity and viscosity of the pore fluid was not measurably different than that of the overlying seawater suggesting considerable transport across the sediment-water interface. Temperature decreased with depth (0-60 cm) in the sediment by nearly 4°C m^{-1}. The temperature gradient measured during SAX04 is the opposite of the gradient measured during SAX99 where the temperature increased with depth by 3-4°C m^{-1}. The decreasing

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temperature gradient suggests a mixing of colder, upwelled water into the sediment to at least 60 cm during Hurricane Ivan, followed by heating of the surface water, and then conduction of heat into the sediment from the overlying water.

In Situ Acoustic Measurements: During SAX04 we used three separate measurement systems to make velocity and attenuation measurements over a frequency range from 0.6 kHz to 400 kHz. The SAX04 measurements built on those conducted during SAX99 by focusing on making accurate measurements at the low end of this frequency range (<20 kHz), where most of the Biot-predicted dispersion occurs and where the SAX99 measurements demonstrated large uncertainties. Two of the measurement systems, covering frequencies from 0.6 to 200 kHz, made in situ measurements of the sands within the first meter below the seafloor. For frequencies below 20 kHz, signals produced by two acoustic sources at a range of offsets and azimuths from the array were recorded on a diver-implanted hydrophone and geophone array. At frequencies from 25 to 200 kHz, we made the measurements using a four probed piezoelectric array (ISSAMS). For comparison at the highest frequencies of 60 to 400 kHz, we measured the velocities and attenuation of 5 diver-collected cores with 4 separate pairs of oil-filled, peizoelectric transducers. Initial results for the sound speed measurements demonstrate a very stable acoustic velocity of approximately 1780 m s^{-1} above 10 or 20 kHz. Below 10 kHz the sound speed drops with decreasing frequency in a manner similar to that predicted by Biot theory.

Acoustic scattering experiments from artificially manipulated seafloor surfaces: Divers set up nine 2-m-by-2-m treatment areas within the acoustic field of view of the 40-kHz APL Bottom-mounted Autonomous Measurement System (BAMS). Treatments consisted of varying abundances of glass spheres (10–80 m^{-2} abundances of marbles with 1.75-cm radii) and aluminum disks (10–80 m^{-2} abundances of 5-cm-diameter, 0.2-cm-thick disks provided by Tim Stanton, WHOI). The aluminum disks, meant to replicate small sand dollars, were placed either in horizontal or vertical orientations relative to the sediment surface. The quasi-periodic ripple fields were raked by divers using a straight-edge surface milled to create tine spacings (ripple wavelength) of 1.91-cm and 3.0-cm. Ripple fields were created parallel (180°), perpendicular (90°) and at a 30° angle to the incident path of the acoustic waves. Hurricane Ivan (September 15-17, 2004) delayed the deployment of the BAMS tower until September and divers were not able to begin establishing the treatment areas until 27 September. Most of the initial experiments were conducted in conditions of very poor visibility (less than 30 cm). Mud deposited on the seafloor after Hurricane Ivan and resuspended during the resurrected remnants of Hurricane Ivan (September 24-25) and Tropical Storm Jeanne (September 26-27) created scattered surface mud deposits a few to tens of centimeters thick. Several surface scattering experiments became volume scattering experiments after the glass spheres and aluminum disks disappeared below the sediment surface. A later storm (Tropical Storm Matthew, September 10) covered the muddy deposits with sand creating flaser deposits with imbedded glass spheres and aluminum disks. The acoustic measurements were terminated on October 6, when there was a failure of the BAMS tower. In spite of the experimental difficulties some preliminary conclusions can be drawn from acoustic images collected by BAMS. In no cases were the aluminum sand dollar replicates visible in the scattering images. Glass spheres were evident in most acoustic images at all levels of abundance. Scattering strengths decreased with time as the glass spheres became buried. After the experiments were completed, almost all of the glass spheres and aluminum disks were recovered by divers from the treatment areas, suggesting any changes in measurement backscatter strengths were not due to the loss of potential targets. Treatment areas that were raked with a 1.91-cm tine spacing perpendicular to the acoustic path had strong backscatter strengths which decayed rapidly with time. Treatment areas raked with 3.0-cm tine spacing had much lower scattering strengths. Treatment areas raked with either tine spacing (1.91- or 3.0-cm) at 180° or 30° to the incident acoustic path were not notably different that

untreated areas. A second set of manipulative experiments was conducted using glass spheres and raked surfaces in the acoustic field of view of transducers mounted on the APL rail system. Two experimental treatment areas were established 10 m from the base of the rail system. Backscattering strengths (20-150 kHz) were measured as divers increased the abundance of glass spheres from 10 to 80 m^{-2} and raked the other treatment area with a tine spacing of 1.91 cm at 30°, perpendicular and parallel to the path of the incident acoustic waves. These experiments were conducted in conditions of excellent visibility and the initial analyses of the data suggest good agreement between acoustic theory and measurements.

Seafloor Roughness/Photogrammetry: Bottom roughness (meter to mm scales) was measured by diver-operated stereo analog cameras when water clarity permitted on October 16 and 26. Of the 30 stereo pairs collected, perhaps 20 have sufficient image clarity to permit analysis; only one stereo pair has been analyzed to date and the 1D roughness power spectra estimated from these data have average slope and intercept values of -3.21 and 2.11×10^{-4}, respectively, similar to initial values for rippled sand at SAX99. Divers made pencil traces of the seabed on Mylar sheets, on sand and mud interfaces, at north, east, and northwest orientations throughout the experiment. The maximum (steepest) and minimum spectrum slopes for north-south traces were -3.35 and -2.70, respectively. The maximum (steepest) and minimum spectrum slopes for east-west traces were -3.16 and -2.61, respectively. The rms roughness values varied from 0.39 to 1.62 cm, with an average rms value of 0.95 cm.

IMPACT/APPLICATIONS

Understanding and modeling the phenomena of penetration of high-frequency sound at low grazing angles into the sea floor will aid in mine detection and classification for the navy.

TRANSITIONS

The results of this basic research are used in developing acoustic models for seafloor scattering. The database is potentially useful for inclusion in the NAVOCEANO shallow-water MIW sediment database.

RELATED PROJECTS

NRL has a companion 6.2 base program on high-frequency acoustic seafloor interactions. ONR Ripples DRI experiments were conducted concurrently with the SAX04 experiments. Todd Holland's Heterogeneous Environments ARO is being conducted in the same general area in the northeastern Gulf of Mexico. ONR's Mine Burial Processes (MBP) 6.2 program is indirectly related to this 6.1 research. Predicting burial state of mines on the sea floor is another facet of information, along with the acoustic predictions for scattering strength of seafloor targets, in the decision process in mine hunting.

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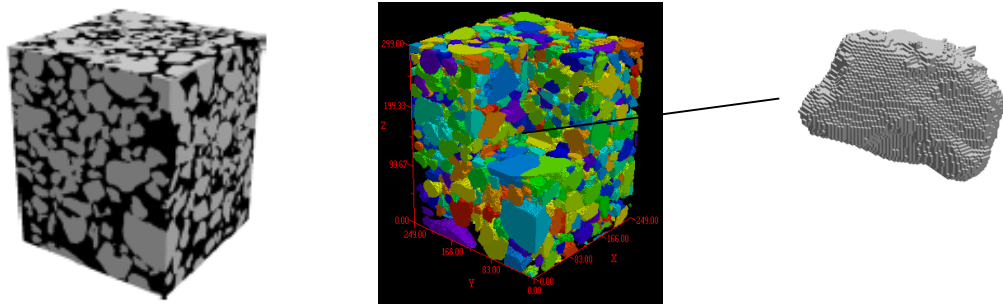
Figure 1. CT scan of resin-impregnated sediment collected with a diver core during SAX04. The volume of scanned sediment is 82 mm³ with a calculated porosity of 39%. Pore network parameters are a mean inscribed pore radius of 59 μm, a mean inscribed throat radius of 42 μm, and a mean pore coordination number of 6.0. The individual grain has a volume of 2.52×10⁸ μm³, surface area of 2.0×10⁶ μm² and aspect ratio of 2.2.